Heterogeneity in time-space synaesthesia: Implications for attention cued paradigms

by

Siren Tønnesen

Master of Philosophy in Psychology

Cognitive Neuroscience

Department of Psychology

UNIVERSITY OF OSLO

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Abstract

People who have time-space synaesthtesia experience a spatial location for the units of time (e.g. days of the week or months of the year; Jarick et al., 2011). The synaesthtetic sensations have been found to influence and direct spatial attention (Smilek, Callejas, Dixon, & Merikle, 2007). Recent studies have also reported superior visuo-spatial memory in time-space synaesthetes compared to controls (Simner, Mayo, & Spiller, 2009). Though, heterogeneity and individual differences within the time-space synaesthetes and attentional load may influence the synaesthtic sensation (Brang, Teuscher, Ramachandran, & Coulson, 2010; Mattingley, Payne & Rich, 2006). To test if attentional load and heterogeneity within the time-space synaesthetes would influence the synaethtetic sensation we employed a spatial cuing paradigm with an interleaving task with varying levels of difficulty. We also predicted that time-space synaesthetes would have superior visuo-spatial memory. Pupillomitry was used in conjuction with behavioural data to assess the cognitive load. We reported evidence indicating heterogeneity and individual differences within the time-space synaesthetes which influence the synaesthtic sensation. Furthermore, our findings indicate that increased attentional load can influence (decrease) the synaesthtetic experience. We did not observe enhanced visuo-spatial abilities in time-space synaethtes.

Introduction

It was Francis Galton (1880) who first reported on the phenomenon of synaesthesia and described how some people have the ability to visualise numbers as having a spatial location. Synaesthesia is typically considered to be a condition in which certain sensory stimulus in one modality may induce vivid sensations in the same or in another sensory modality (Mattingley et al., 2001). For instance people may “hear” colours; that is, they get a sensory experience of colour when they listen to music (Simner, Mayo, et al., 2009). These illusory perceptions are not hallucinatory, i.e. the subjects know the perception does not reflect the external sensory stimulation (Specht & Laeng, 2011). Recently a multitude of types of synaesthesia has been identified, including sounds that are elicited by viewing moving patters (Saenz & Koch, 2008) and words may elicit taste (Ward & Simner, 2003). An interesting aspect with synaesthesia is that the phenomenon has been found to modulate attention (Laeng, Svartdal & Oelmann, 2004; Mattingley, Payne & Rich, 2006) and that people with synaesthesia may benefit in terms of enhanced memory (Mann, Korzenko, Carriere, & Dixon, 2009; Simner, Mayo, et al., 2009). Accordingly, it has been noted that time-space synaesthesia is a “gift” and that people who have this type of synaesthesia have increased temporal and visuo-spatial memory (Rothen, Meier, & Ward, 2012; Simner, Mayo, et al., 2009). The majority of research on attention and memory of time-space synaesthetes has focused on behavioural measures such as response times. Non-invasive physiological measures such as pupillary responses might offer additional insight and understanding of the mechanisms related to synaesthesia (Paulsen & Laeng, 2006). For instance, pupillary change as a function of task-evoked attentional capacity has been used to index cognitive load or “mental effort” (Hess & Polt, 1964; Kahneman & Beatty, 1966). Thus, pupillary responses may add some incremental understanding, in conjunction with reaction time and behavioural measures, of the synaesthetic experience.

Synaesthesia: an overview

It is estimated that the prevalence of synaesthesia in the normal population is around 4% (Simner et al., 2006). Though, different studies have yielded rather different estimates with estimates of 0.05% (Baron-Cohen, Burt, Smith-Laittan, Harrison, & Bolton, 1996) or lower (Rich, Bradshaw, & Mattingley, 2005) . Synaesthesia has an early onset in life (Simner, Harrold, Creed, Monro, & Foulkes, 2009) and the consistency of the synaesthetic experience is high throughout the lifespan (Specht, 2012). It is important to stress that synaesthesia is not a disorder as it not associated with general cognitive dysfunction, brain pathology, psychological, neurological or psychiatric diseases (Bargary & Mitchell, 2008).

The synaesthetic experience is typically considered to be an effortless, automatic and consistent experience where an inducer (the triggering sensory stimulus) results in an elicited synaesthetic experience (a concurrent) (Grossenbacher & Lovelace, 2001). Though, it has been reported that the synaesthetic inducer may require a focal attention to exert its influence (e.g., a visual angle of approximately 5º in some individuals; Laeng et al., 2004). A finding which indicates that the synaesthetic inducer is not directly comparable to basic perceptual stimuli (e.g. colours). The synaesthetic experience does not occur at a preattentive stage of processing, at least for grapheme-colour synaesthesia (where alphanumeric symbols trigger colour experiences), as the phenomenon of very efficient visual searches - or even “pop out” effects would suggest; rather it requires attention or focus of the target/stimuli (Laeng et al., 2004). The synaesthetic experience, however, should be stable over time and occur without voluntarily control. Furthermore, synaesthesia differentiates itself from learned associations as it cannot be trained (Specht, 2012) and it is therefore considered to a percept-like phenomenon rather than a mental association (Rothen et al., 2012). Though, a study by Meier and Rothen (2009) reported that non-synaesthetes who were trained 10 min a day for 7 consecutive days to associate graphemes with colours elicited a synaesthetic Stroop effect. Though, this effect diminished after one week without training and neither of the controls reported that the letters triggered an experience of colour. It is evident that there is the consistency and perceptual experience is unique about synaesthesia and differentiates synaesthetes from non-synaesthetes.

Furthermore, the synesthetic experience is considered to be most *often* unidirectional than bidirectional (e.g. music trigger colours, numbers trigger colours and not vice versa; (Rothen & Meier, 2010). Though, recent studies indicate that the synaesthesia may be bidirectional and colours may, for example, influence lexical search (Weiss, Kalckert, & Fink, 2009). The directionality of the synaesthetic experience might be constrained or influenced by evolution or neural hierarchy (Ramachandran & Hubbard, 2001). Thus it is often unidirectional even though there are reports of bidirectional relationships.

As previously noted, there are various forms of synaesthesia. Some authors (e.g. Ward & Simner, 2005) reported that the most reported form is grapheme-colour synaesthesia, and it has been estimated a prevalence of 1% in the normal population(Simner et al., 2006). However, recent estimates indicate that day-colour synaesthesia has a prevalence of 64 % within the synaesthetic population and therefore might seem to be the most common (Simner et al., 2006). However, synaesthetes often have more than one form of synaesthtesia and the co-occurrence two and more forms of synaesthtesia is quite high (Ward & Simner, 2005). People who have grapheme-colour synaesthesia perceive colours for written letters and/or digits (Rouw & Scholte, 2007). For instance, the letter B always elicits “blue” irrespective of the colour the letter is typed in. This study, however, will focus on time-space synaesthesia (also referred to as visuo-spatial synaesthesia), perhaps the most common form of synaesthesia, where people experience a spatial layout for days, weeks, months or years (Jarick, Jensen, Dixon, & Smilek, 2011). For instance, the months, days, years or centuries occupy a spatial location. For example, the months of a year may be spatially represented around the synaesthete’s body. It can either be perceived as 3D (outside one’s body) or in a “mental space” as see with the “mind’s eye” (Simner, Mayo, et al., 2009). Synaesthetes who experiencing the synaesthetic sensation outside one’s body is often referred to as ‘projectors’, whilst the synaesthetes who see with their “mind’s eye” are referred to as ‘associators’ (Dixon, Smilek, Merikle, 2004). Please see Figure 1 for an illustration of how projectors and associators might perceive their synaesthtetic colour for ‘A’ and ‘B’.

Figure 1. An illustration of the difference in perception between ‘projectors’ and ‘associators’. Adapted from “Effective connectivity determines the nature of subjective experience in grapheme-color synaesthesia,” by T. M. van Leeuwen, H. E. den Ouden, and P. Hagoort, 2011, *Journal of Neuroscience*, 31, p.9880.

Time-space synaesthesia

The prevalence of time-space synaesthesia has been estimated to be a conservative 2.2% (Brang, Teuscher, Ramachandran, & Coulson, 2010). Time-space synaesthesia differentiates itself from the other forms of synaesthetic experiences as the experience is not triggered by external sensory stimulation (Specht, 2012). In contrast, it is semantic information, usually a unit of time, such as a day of the week, or a month of the year that triggers the synaesthetic experience (Jarick et al., 2011; Mann et al., 2009; Simner, Mayo, et al., 2009). Conversely, Santiago, Lupianez, Perez, and Funes (2007) suggested that time and space associations are found either implicit or explicit in all people. These associations are found not only within cultures but also across cultures. Furthermore, (Bonato, Zori, & Umiltà, 2012) noted that time and space are not processed separately, but time is represented as space. Linguistic expressions such as "back in the day" support the notion that time and space are sometimes processed together. Past events are often related to the left or anterior space whereas future events to right or front space (Bonato et al., 2012). Thus, it is not surprising that Jarick, Dixon, Stewart, Maxwell, and Smilek (2009) reported that there is a debate as to whether time-space synaesthesia is truly a form of synaesthesia. It might be that this is a phenomenon that is found to some extent in all people, already as infants (Walker et al., 2010), and perhaps even in apes (Humphrey, 2012). However, the debate is current for synaesthesia in general. One might argue that all forms of synaesthesia exist in all people as a spontaneous across-modality matching (e.g. people know what a 'bright sound' or a 'loud shirt' is). Studies have also shown that people can differentiate whether a form should called 'takete' or 'maluma' (Köhler, 1929, as cited by Nielsen & Drew, 2011), or more recently differentiate whether a shape is Bouba or Kiki (Gallace, Boschin, & Spence, 2010). However, Mann et al. (2009) suggested that synaesthesia might not be an 'all or nothing' phenomenon. Their findings indicated that synaesthesia might be more a continuous phenomenon. Furthermore, it has been reported that there are a certain amount of individual differences between synaesthetes and there is heterogeneity within this group (Brang et al., 2010). Though, Brang and Ramachandran (2008) debated the genetic expression in relation to synaesthesia, as a trait that is either present or absent. Still, there might be continuous variations in the trait 'synaesthesia' even if it has a genetic expression. This variation might be related to a certain thresholds; the developmental trajectories might be triggered if the genetic expression is either below or above the thresholds (Ward & Simner, 2005).

Although it is conceivable that synaesthesia is on a continuum and that it is presented is some form in all people. There might be differences between people who define themselves as synaesthetes and the rest. This is evident in behavioral data such as RT and presentations of the synasthetic sensation. For instance, wwhen tested, non-synaesthetes produced the traditional clock face when asked to align the hours of the day (Jarick et al., 2011) and in this study, the non-synaesthetes often aligned the months of the calendar in a linear fashion. Though, the difference between non-synaesthetes and time-space synaesthetes is that the latter group often has more elaborate, idiosyncratic and vivid perceptions than the former (Jarick et al., 2011). In addition, synaesthetes are more consciously aware of the spatial perception compared to non-synaesthetes and the layouts of the spatial forms for synaesthetes are often more elaborated in comparison to non-synaesthetes (Sagiv, Simner, Collins, Butterworth, & Ward, 2006).

Previous studies also support the existence of time-space with findings indicating that the synaesthetic experience influences spatial attention (Smilek et al., 2007) and generates a month spatial-numerical association of response codes (SNARC) effect (Price & Mentzoni, 2008). The "month SNARC" was adapted from the SNARC effect described by Dehaene, Bossini, and Giraux (1993). The original SNARC effect is best described as an advantage with left (right) hand for ordinal sequences that are early (late) in the spatial layout. The altered SNARC test (i.e. the month SNARC test) was used to assess the spatial layout time-space synaesthetes' calendar. The finding indicated a faster left (right) hand reaction time for synaesthetes who month's experienced months on their left (right) spatial representation. The results are comparable to the Posner cueing-paradigm, which will be discussed in subsequent sections.

In conjunction, these studies support the idea that time-space synaesthesia is a true form of synaesthesia, though it sensation might be on a continuum and there will be individual differences and heterogeneity within this group.

Time-space and visuo-spatial memory

Remarkably, Brang et al. (2010) reported that time-space synaesthetes were better at learning a novel spatial calendar compared to non-synaesthetes. This suggests that synaesthetes might have superior visual-spatial memory. Furthermore, it has been noted that time-space synaesthesia is a "gift" and that people who have this type of synaesthesia may benefit in form of superior performance in temporal and visuo-spatial test (Simner, Mayo, et al., 2009). It is therefore not surprising that people with synaesthesia have been found to have enhanced memory abilities (Rothen et al., 2012). A multitude of studies has reported the synaesthetes' superior abilities on a range of assessments, including memory for abstract figures (Rothen & Meier in Rothen) and visuo-spatial memory tests (Simner, Mayo, et al., 2009). Case studies have also indicated that synaesthetes might have enhanced memory for digit span(Rothen & Meier, 2009) and digit matrices(Smilek, Dixon, Cudahy, & Merikle, 2002). Though, studies using a larger sample size have not been able to replicate these results (Yaro & Ward, 2007).

Simner, Mayo, et al. (2009) found that synaesthetes were better, compared to the control group, in all of the assessments related to their synaesthetic experience. However, the synaesthetes' performance on assessment unrelated to the synaesthetic abilities was comparable to that of the control group. One of the tests that were employed was the Visuo-Spatial Patterns Test (VPT; (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999)) which is a test of visuo-spatial memory. Conversely, Simner, Mayo, et al. (2009) examined a small sample size which comprised of only four synaesthetes. To further validate and strengthen the results we therefore choose the VPT in this experiment. Despite encouraging results of synaesthetes superior performance, Rothen and Meier (2010) reported that the general and task specific memory abilities of synaesthetes are not superior but within the normal range. They noted that time-space synaesthetes generally score better on visuo-spatial tests than other memory tasks whereas non-synaesthetes score evenly across all tests (Rothen et al., 2012). Furthermore, there has also been reported that there might be "costs" associated to the cognitive advantages synaesthetes might have. For example, when the external stimuli are not related to the synaesthetic experience, the synaesthetes may use less flexible strategies to solve the tasks. Performance improved when stimuli were consistent with the synaesthetic experience (Smilek et al., 2007). It is reasonable to argue that the synaesthetic experience might also interfere and encumber performance on certain tasks where the external stimuli are unrelated to the synaesthetic expression. However, as presented, there is converging evidence that time-space synaesthetes might have a cognitive advantage in task specific tests, but only within the normal range. We therefore predict that time-space synaesthetes will perform to an equal degree on a non visual-spatial test.

Time-space synaesthesia and attention

Previous studies has reported that time-space synaesthetes experience that thinking of a month of the year often automatically directs their attention to the associated spatial position (Jarick et al., 2009; Smilek et al., 2007). This might be an indication that the months might be used to bias or direct visual attention (Smilek et al., 2007). The study by Smilek et al. (2007) supported the notion that time units may direct and bias the visual attention of synaesthetes. They employed an attentional cueing paradigm to explore the visual attention of time-space synaesthetes and non-synaesthetes. The cuing paradigm (e.g. see Posner & Petersen, 1990) is a test of shifts of spatial attention, or in other words, allocation of the focus of attention in space. Traditionally the participants indicate the location or identity (e.g. identify the letter) of a target that is preceding a cue. The cue can either indicate the correct location of the target (valid) or the incorrect location (invalid), or be neutral. The difference in reaction times between the three conditions is used as an index of how much target detection is influenced by the spatial cuing. In the study by Smilek et al. (2007), the participants were presented with visual cues (i.e. word of a month of the year) that were either predictive of a target (valid) or non-predictive of a target (invalid). It was the synaesthetes' spatial representation of the year that determined whether the month was predictive or non-predictive of the target. For example, if a synaesthete reported that August was to the left then the word 'August' would be non-predictive (invalid) for a target appearing on the right side of the screen; although, it would predictive (valid) for a target appearing on the left side. The stimulus-onset asynchrony (SOA) can also be manipulated to assess how quickly the cue might influence attention. The SOA was either short (150 ms) or long (600ms). Since the invalid month cues biased a synaesthetes' visual attention irrespective of the SOA the results indicated that the month cues may bias visual attention rapidly and independent of the synaesthetes' intentions. Smilek et al. (2007) concluded that the cues influenced attention in a reflexive manner since the effect was found regardless whether there was a long cue-target SOA (600 ms) or a short cue-target SOA (150 ms). This might suggest that the month cue acts as a salient stimulus and that it is the exogenous, or stimulus-driven, attentional pathway that is activated. The exogenous, or bottom-up network, is driven by salient stimuli that are attention-grabbing (Buschman & Miller, 2007).

The findings from Smilek et al. (2007) were replicated and validated by a case study of Jarick et al. (2009). Adding to the work of Smilek et al. (2007), they reported that also auditory cue stimuli may bias visual spatial attention. However, the modality of the inducer (visual or auditory) was found to influence the mental vantage point of the participant's calendar and that the "mental vantage point" could shift depending on the preceding cue. Thus, the vantage point from which the person "sees" the calendar may change as a function of the cues. In order to accurately measure the spatial position relative to the person's body it would also seem important to "reset" the calendar in-between trials. In fact, the month cues in the attentional cueing paradigm might shift the mental vantage point for the synaesthetes throughout the test. Thus, a valid month cue might not be regarded as 'valid' later in the trials. This might pose as a problem when either coding the cues as valid/invalid or interpreting the results. However, the issue might be overcome if it were possible to 'reset' the calendar between each month cue trial. Due to the nature of the time-space synaesthetic experience the task used to reset the calendar should draw on similar resources in an attempt to 'free' the synaesthetes from their focus on months. For this purpose a visuo-spatial task such as Tower of London (TOL) can be used. In other words, we assume that attentional and memory processes needed for solving TOL would “free” the synaesthetes from their current focus on the spatial time cues and perhaps their present “location” in their spatial calendar. Indeed,Cheetham, Rahm, Kaller, and Unterrainer (2012) suggested that the TOL primarily rely on visuo-spatial processing. Thus, it is reasonable to argue it is a suitable test for resetting the synaesthetes’ calendar between each month-cue trial.

The TOL was initially developed with the aim of testing subtle deficits in behaviour, such as frontal lobe damages, in addition to assessing executive planning ability (Shallice, 1982). The test involves mentally manipulating images of six balls positioned on two rows with three vertical rods. There are three differently coloured balls located placed on three rods. The task is to mentally manipulate the images and count the least number of times one has to move the ball(s) in order for the two images to become identical. The number of moves required determines the level difficulty of each individual trial. The number of moves normally ranges between 2 and 5 steps.

By using the TOL one can examine whether time-space synaesthetes have superior memory capabilities compared to non-synaesthetes. The data obtained from the eye tracking method will supplement the behavioural data from the memory test. Of particular interest is the number of fixations as it the mean number of fixations should increase as a function of level of difficulty; i.e., additional imaginary moves, required in the difficult trials, should require an increasing number of fixations.

Synaesthesia and executive function

Synaesthetes are, in comparison to people who have hallucinations and delusions, aware that their synaesthetic experience is not a ‘real’ perception, but rather an extra perception of the stimuli (Rouw, van Driel, Knip, & Richard Ridderinkhof, 2013). However, these two perceptions are different and might perhaps be in conflict with each other, e.g. a letter written in black (‘real’ colour) may elicit the perception of the letter being yellow (synaesthetic colour). Furthermore, it is interesting that the two contrasting perceptions may share the same (external) space (Dixon, Smilek, & Merikle, 2004; Rouw & Scholte, 2010). Synaesthetes display an ability to manage and control the opposing perceptions. The management of perceptions is evident in the adapted version of the Stroop task (MacLeod, 1991; Stroop, 1935), i.e. the synaesthetic Stroop task, where synaesthetes make few errors (Berteletti, Hubbard, & Zorzi, 2010). In the standard Stroop task the participants are presented with a colour word that has a congruent or incongruent typeface. Naming the word tends to be slower for the incongruent compared to the congruent condition. For the synaesthetic Stroop task the synaesthetes are presented with a grapheme that is either in a typeface congruent or incongruent to their synaesthetic colour. The error rate is quite low, though the RT time tends to be slower for the incongruent condition suggesting a conflict between the 'real' and synaesthetic perception (Berteletti et al., 2010). However, there might be some managing mechanisms involved in resolving the (possibly) conflicting perceptions since the error rate is quite low (Rouw et al., 2013). Rouw et al. (2013) suggested it could be related to executive control functions. In other words, the management and control of the perceptual inference generated by synaesthetic experience is similar to the mechanisms of general executive functions. Rouw et al. (2013) aimed to explore the executive functions of synaesthetes. In general, the synaesthetes did not display any increased executive functioning in comparison to the control group. Furthermore, the results indicated that the perceptual inference synaesthetes encounter is not managed by executive control. Additionally, their findings suggest that synaesthetes may choose to neglect or ignore the synaesthetic perception. The synaesthetes may present with a control function that is specific to selective suppression of the synaesthetic sensations.

Mattingley et al. (2006) asked synaesthetes and non-synaesthetes to perform dual-task where the trials included alternation between a synaesthetic Stroop task and an attentional load task. The synaesthetes displayed a congruent effect for naming the colour of the letter, though the effect was reduced under high-load compared to low-load. They interpreted the result in terms of the essential role attention holds in relation to modulate the synaesthetic experience. Furthermore, it was suggested that during attention-demanding tasks the synaesthetic sensations might be weak or absent.

In relation to performing dual-tasks,Cheetham et al. (2012) reported that the TOL task interfered with and reduced the performance on a dual-task tapping the visuo-spatial memory. Furthermore, in the dual-task manipulation, the processing of TOL had a negative influence on solving the visuo-spatial memory task. However, interestingly, the memory performance did not decline as a direct function of increasing difficulty of TOL. There was a linear relationship, but the most difficult level did not result in the greatest impairment in relation to memory performance. Conversely, it was the second most difficult level that proved to moderate the visual-spatial memory the most.

In conjunction, these results indicate that the synaesthetic sensation might diminish or be absent in a dual-task paradigm. The findings from Mattingley et al. (2006) indicated that the synaesthetic experience should weaken as a function of level of TOL. While the findings from Cheetham also suggests that the increasing level of TOL should moderate the sensations, but the relationship between decline in sensation and level of difficulty might reach some sort of plateau. Thus, we expect to the validity effect to diminish at the most difficult levels of TOL. Though, it is unclear whether the reduction will be displayed as function of level of TOL. Furthermore, if the synaesthetic sensation is diminished it might indicate that synaesthetes have a control mechanism which allows them to suppress the synaesthetic perception that generates the perceptual interference.

In the current study we wanted to assess how executive functions in synaesthetes and explore whether synaesthetes do have a control mechanisms that reduce the synaesthetic sensation if the attentional load gets too high. Therefore we manipulated the attentional load by introducing an interleaving test (TOL) with varying levels of difficulties between each cued month trial.

Eye tracking and shifts in attention

Measuring eye movements and pupil dilation is a non-invasive procedure. The most common method of eye tracking nowadays is to use infrared light in order to illuminate the eye and then measure the reflection using a charge-coupled device (CCD) array of a digital video camera that is only sensitive to infrared light (Henderson, 2006). Typically, changes in pupil size, saccades and fixations are recorded using an eye tracker. Stabilization of gaze on an object is considered to be a ‘fixation’ (Duchowski, 2007). It has been estimated that people fixate their eyes around 90% of their viewing time. In contrast, saccades are related to directing visual attention to a new area, and this is manifested with fast eye movements and repositioning of the fovea onto a new area (Duchowski, 2007). In general, the acquired data and pupil dilation may reflect on-going visual and cognitive processing (Henderson, 2006). 2006) and it has been widely used as an index of arousal and interest (Demos, Kelley, Ryan, Davis, & Whalen, 2008). Pupil dilatation has been often reported in response to emotional arousing stimuli such as such images containing illusions of sexually related content (Laeng, Sirois, Gredebäck, 2012). Pupil dilation has not only been found for emotionally pleasing stimuli, it has also been reported during the exposure to potentially threatening stimuli (Chapman, Oka, Bradshaw, Jacobson, & Donaldson, 1999).

In 1964, Hess and Polt recorded pupillary reactions while participants solved mathematical problems. The results suggested an increase in pupil size as a rather linear function of the level of difficulty of the problems. In a similar study, Kahneman and Beatty (1966) requested participants to remember strings of verbally presented digits. The results indicated a gradual increase in pupil change as subsequently numbers were added to the string. These findings in combination indicate that pupillary responses reflect cognitive processing load (Kahneman, 1973). Thus, pupillary size is predicted to increase as a function of increasing load on memory. In contrast to changes in ambient light, which may result in doubling the pupil size, cognitively driven changes on the pupil size are mostly modest and not often greater than 0.5 mm (Beatty & Lucero-Wagoner, 2000; Laeng, Sirois, & Gredebäck, 2012).

Pupillary responses have been used previously in research with grapheme-colour synaesthetes. It was reported that the pupillary size increases more for incongruent coloured words than for congruently coloured letters in a Stroop-like situation (Paulsen & Laeng, 2006). Specifically, when synaesthetes viewed incongruently coloured single-letters their pupils dilated more than when they viewed congruently coloured single-letters. This supports the idea that synaesthesia is percept-like and has an influence on the attentional system.

In relation to the current study, pupil dilation can be used to not only measure the mental effort experienced during the cognitive memory tasks but also during the attentional cueing paradigm. The behavioural results as indexed by reaction times suggest that identifying an invalidly cued target might require a greater effort than a validly cued target since there is a conflict in the former situation.

Eye movements and mental imagery

Intuitively, the VPT may require mental imagery. It has been (and still are) debated whether eye movements have a functional role in relation to mental imagery (e.g. see Mast & Kosslyn, 2002). In order to discuss eye movements during mental imagery, one needs to understand the mechanisms underlying eye movements during visual perception. The illusion of perceiving a scene sharply is generated by the eye movements, since we only perceive high resolution of the image that falls on the central foveal region of the retina (Mast & Kosslyn, 2002). Thus, eye movements are pertinent for visual perception and they are not entirely random. The mechanisms that govern the eye movements can broadly be divided into two: bottom-up and top down (Harding & Bloj, 2010). Bottom-up processes respond to low-level image features, e.g. luminance, contrast, and colour, which might be generated by sudden changes in the visual scene. Top-down process, on the other hand, govern eye movements by prior knowledge and expectations (Harding & Bloj, 2010). Mast and Kosslyn (2002) noted that top-down processing is still at the brink of being unravelled and that studying eye movements during mental imagery might offer some additional insight. Bruno Laeng and Teodorescu (2002) examined eye movements during mental imagery and their findings indicated that eye movements have a functional role in relation to mental imagery. The participants were asked to view a 6x6 grid pattern, similar to the 'checkerboard' matrix used for the VPT. The participants would view the 'checkerboard' for a fixed period time, then they were asked to form a mental imagery of the stimuli before a spatial memory test of the 'checkerboard'. In the perceptual phase five of the grids on the 'checkerboard' were filled in with black; whilst in the spatial memory test all the grids where white. The participants would have to judge the position of the previously black grids. Their results indicated that the order of scanpath during the perceptual phase was highly correlated with the scanpath during the imagery phase. Thus, Laeng and Teodorescu (2002) suggested that eye movements do have a functional role during image generation; meaning that the ocolumotor activity is not irrelevant during mental imagery (Hebb, 1968). Hence, we introduced an interleaving task (bouncing ball) in the VPT. This was to disrupt ant "rehearsal" (i.e. oculomotor activity during mental imagery) of the positions of the black grids presented during the perceptual phase.

Current study

In order to extend previous research on the phenomenon of time-space synaesthesia, the present study assessed whether aurally presented cues are effective in biasing visual spatial attention in time-space synaesthetes. Furthermore, we examined their difference in performance on visuo-spatial tasks compared to non-synaesthetes. The experiment comprised: a) a spatial cuing paradigm, b) a visuo-spatial test and c) an arithmetic test. A stationary eye tracker was used to obtain data on saccades, fixations and pupil sizes. Behavioural data such as correct response and response times (RTs) was also recorded.

Previous studies have often been either case studies or conducted on a small sample of selected synaesthetes (e.g. Smilek et al. (2007) with an *N*=28 and only 4 synaesthetes). As previously noted, there can be heterogeneity among synaesthetes and large individual differences and findings might be different if a larger sample is tested. Furthermore, no previous study attempted to 'reset' the spatial calendar between each month cue trial. In addition, previous studies using cued paradigm in relation to time-space synaesthetes have only assessed behavioural measures. Thus, the current study might offer additional insight in relation to the underpinnings of time-space synaesthetes since pupillometry data also will be analysed. Finally, we extend the work by Jarick et al. (2009) by using auditory presented cues on a larger sample size of participants.

Hypotheses

Spatial consistency

It was hypothesised that the synaesthetes would have a consistent and reliable test-retest spatial representation of their calendars. Though, we expected to see a certain degree of individual differences within the synaesthetic group and that there would be some synaesthetes that are more ‘reliable’ (i.e. their synaesthetic expression is stronger) than other synaesthetes. Furthermore, we also anticipated that there might be individual difference and heterogeneity in the synaesthetic sample and not all synaesthetes would display a cueing effect. However, we expected that only synaesthetes would show a cuing effect, in the expected direction (i.e. longer RT for the incongruent month cues compared to the congruent month cues), and that none of the controls would show a cuing effect.

Visuo-spatial test and mathematical test

We predicted that synaesthetes would perform better than controls on the visuo-spatial tests, VPT, whereas there would be no difference between the groups on the mathematical task. Furthermore, it was hypothesised that if synaesthetes were better at the VPT compared to controls, the groups would differ in relation to pupil change. However, both groups should display a similar pattern of cognitive load on the mathematical task. A non-significant difference in cognitive load may also suggest that motivation to do the tests do not differ between the groups.

Cued-month and TOL

We also hypothesised that synaesthetes would be faster at detecting the targets on valid trials than on invalid trials. In comparison, there should be no cuing effect of the month cues for the control participants. Furthermore, it was anticipated that the level of TOL would influence the cueing effect in terms of a reduced effect in relation to increasing levels of TOL. It was anticipated that this relationship would not be observed in control. The linear relationship for cuing effect and level of TOL was hypothesised to be significantly different due to the influence of executive function or attentional load on the synaesthetic sensation.

It was also predicted that there would be an increasing number of fixations as a function of TOL, despite the inverse relationship between cognitive load and pupil dilation.

Method

Participants

Thirty-five participants (21 time-space synaesthete and 14 non-synaesthetes) were recruited from the University of Oslo, via acquaintances and social media (i.e. Facebook). Please see Table 1 for an overview of the sample. They were asked to perform on four tasks; three of which included recording pupil data. The sample comprised synaesthetes that were between 19 and 45 years of age (*M*=29.6, SD=5.89) whereas the controls were between 19 and 35 years of age (*M*=26.4, SD=5.79). All participants had normal or corrected-to-normal vision. A written informed consent was signed before taking part in the study. All participants were compensated with 100 NOK.

Table 1

Overview of the Sample Characteristics

	n	Age M (Range, SD)	Males *n* (% of group)	Education (years) M (Range, SD)
Synaesthetes	21	29.61 (19-45, SD=5.89)	6 (28.57%)	16.62 (14-19, SD=1.39)
Controls	14	26.85 (19-35, SD=5.79)	6 (42.86%)	16.21 (13-19, SD=1.62)

Note. SD=standard deviation, M=mean.

Stimuli and Procedure

Participants were tested individually in a single session in a quiet, windowless, room with constant illumination. The participants were instructed to remain as static as possible during the eye-tracking session. The experimenter remained present throughout the session. Each participant, both synaesthetes and non-synaesthetes, completed a spatial consistency task, an attentional cueing task, the TOL, a multiplication task, and a visuo-spatial memory task. The attentional cuing task, the TOL, the multiplication task and the visuo-spatial memory task were completed in a single session. The exceptions were two non-synaesthetes who had to complete the visuo-spatial memory task at a later stage due to technical issues. Furthermore, the synaesthetes were also asked to repeat the spatial consistency task one to two months after their initial testing. In each of the three eye tracking tasks, the stimuli were equiluminat across all trials.

Setup

Each session lasted approximately 1 hour. Participants were seated at approximately 70cm from the computer screen. Pupil data was acquired using an iView X Hi-Speed eye-tracking device (SensoMotoric Instruments, Berlin Germany). The eye-tracking device is a remote unit which was set on the monitor presenting the stimulus. For all three paradigms, binocular data was recorded at a sampling rate of 60Hz (i.e., pupil size measurements were recorded every 16 ms). The eye-tracking device use infra-red light to capture the reflection of the pupil and the cornea and the system is accurate to less than 0.4 degrees. A 5-point calibration pattern was displayed to participants before running the eye-tracker sessions. A dispersion of <0.5 in both x- and z-space were considered a successful calibration; recalibration was initiated until a successful calibration was obtained.

The stimuli were presented on a 22-inchs creen (Dell, P2210). The paradigms were designed and the stimuli presentation was implemented using SMI Experiment Center® which synchronises the eye-movement recordings to the presentation of the stimuli and keyboard presses. The analyses were conducted using SMI BeGaze® and SPSS®. RTs were recorded using chosen keys on the computer keyboard. The verbal responses were recorded manually by the experimenter. The auditory stimuli were broadcasted over a pair of speakers (Dell, AX210)

Study Design

<u>TOL</u>: The design was a 4 x 2 mixed design, with *Level of Difficulty* (2, 3, 4 or 5 moves) as within-subject factors, and *Group* (synaesthesia, control) as between-group factors.

<u>VPT</u>: The design was a 5 x 2 mixed design, with *Level of Difficulty* (4, 6, 8, 10 or 12 accomplished levels) as within-subject factors, and *Group* (synaesthesia, control) as between-group factors.

<u>Multiplication</u>: The design was a 7 x 2 mixed design, with *Level of Difficulty* (3x4, 4x7, 7x8, 9x15, 8x13, 13x14, and 16x23) as within-subject factors, and *Group* (synaesthesia, control) as between-group factors.

Spatial Consistency Task.

The participants were asked replicate or reproduce their calendar as accurately as possible using Power Point software. They would use the computer-mouse to position 13 circles; one circle being “me” and the other twelve circles for the months. This provided a 2D representation of how their spatial calendar would looks like at the current time of testing and from the synaesthete’s perspective. After a period, varying from one- to two months the participants were asked to repeat the same procedure.

Attentional Cuing and Tower of London task

We adopted a modified version of the Smilek et al. (2007) attentional cuing paradigm. Specifically, in an attempt to reset the calendar between each cuing trial and to test the effects of executive control, every other trial consisted of a mental manipulation tests, i.e. TOL. In other words, trials in the attentional cueing and the Tower of London task alternated one another. The presentation was fixed for each participant. However, the pairing of the month cue and level of difficulty of TOL was randomised prior to setting the fixed presentation.

The participants were informed that they would perform a test consisting of two alternating tasks: a ‘box’-task and mental-manipulation task. In the ‘box’-task there would a black square on either the right side, left side or almost covering the entire screen. Keys were allocated to whether the target appeared on the right (‘b’) or left (‘n’) side of the screen. Participants were required to press either ‘b’ (left) /’n’ (right) using their dominant hand as soon as they detected the target. If the box was covering the entire screen the participants were asked to hold their response. These ‘catch’ trials were included to ensure that the participants were not responding regardless of the targets position. The month cue was presented in a similar manner for all the ‘catch’ trials.

For the alternating task, the Tower of London, participants were asked to mentally manipulate the images and count how many moves that were required to make the images similar. The number of moves ranged from 2 to 5. When the participants had solved the problem they would direct their eyes to the upper right hand of the screen where an area-of-interest (AOI) was created as trigger to inform the experimenter about their answer. Figure 2 illustrates the position of the AOI. In other words, a 300 ms trigger AOI was created in order to reduce the number of response-keys the participants would have to remember and the associated confusion may response-keys might create. The instructions for the TOL were to transform the start space into the goal state within the minimum number of moves. Three rules had to be taken into account: (1) only one ball could be moved at a time, (2) the ball on top had to be removed before the ball underneath could be moved, and (3) a ball could be placed on either rod in a single move. Please refer to Figure 2 for visualisation of the rules.

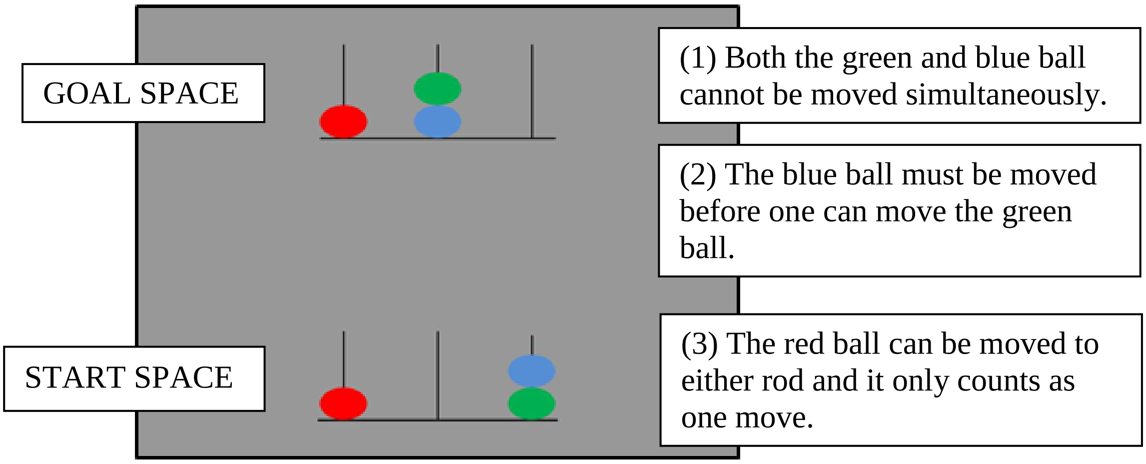

Figure 2. Examples of the Rules for Tower of London

The test comprised 84 pseudo-randomized trials (36 targets on the right side, 36 targets appearing on the left side, and 12 catch trials). The month cues were coded after each session as valid or invalid according to the synaesthetes' spatial representation of the months. Furthermore, the test comprised of 84 TOL trials with respectively 21 trials at level 2, 21 trials at level 3, 22 trials at level 4, and 20 trials at level 5. One of the trials at level 5 was wrongly entered, thus the test comprised of one extra trial at level 4. The luminance was constant throughout all trials irrespective whether the task was a month-cue or TOL.

For an overview of the trials in the TOL/cued paradigm please see Figure 3. The participants were first presented with a centrally located fixation cross for 1000 ms. In order to ensure that fixation was maintained at the centre before each month-cue trial a trigger AOI of 300 ms preceded the verbally presented month-cue. During the cue the stimuli was a centrally located fixation cross. The duration of the month-cue was equal across all conditions at 1200 ms. Following the cue, the boxes would be presented for 3500 ms or until the participant responded. Then a grey screen was presented for 1000 ms, followed by a centrally located fixation cross displayed for 1000 ms. The participants had 15,000 ms to solve the TOL problem. As noted previously, the participants gave their response b fixating at the upper right hand corner of the screen where a trigger AOI (300 ms) was located. At the same time they verbally gave their solutions to the experimenter. The TOL was scored according to the number of correct responses at each level.

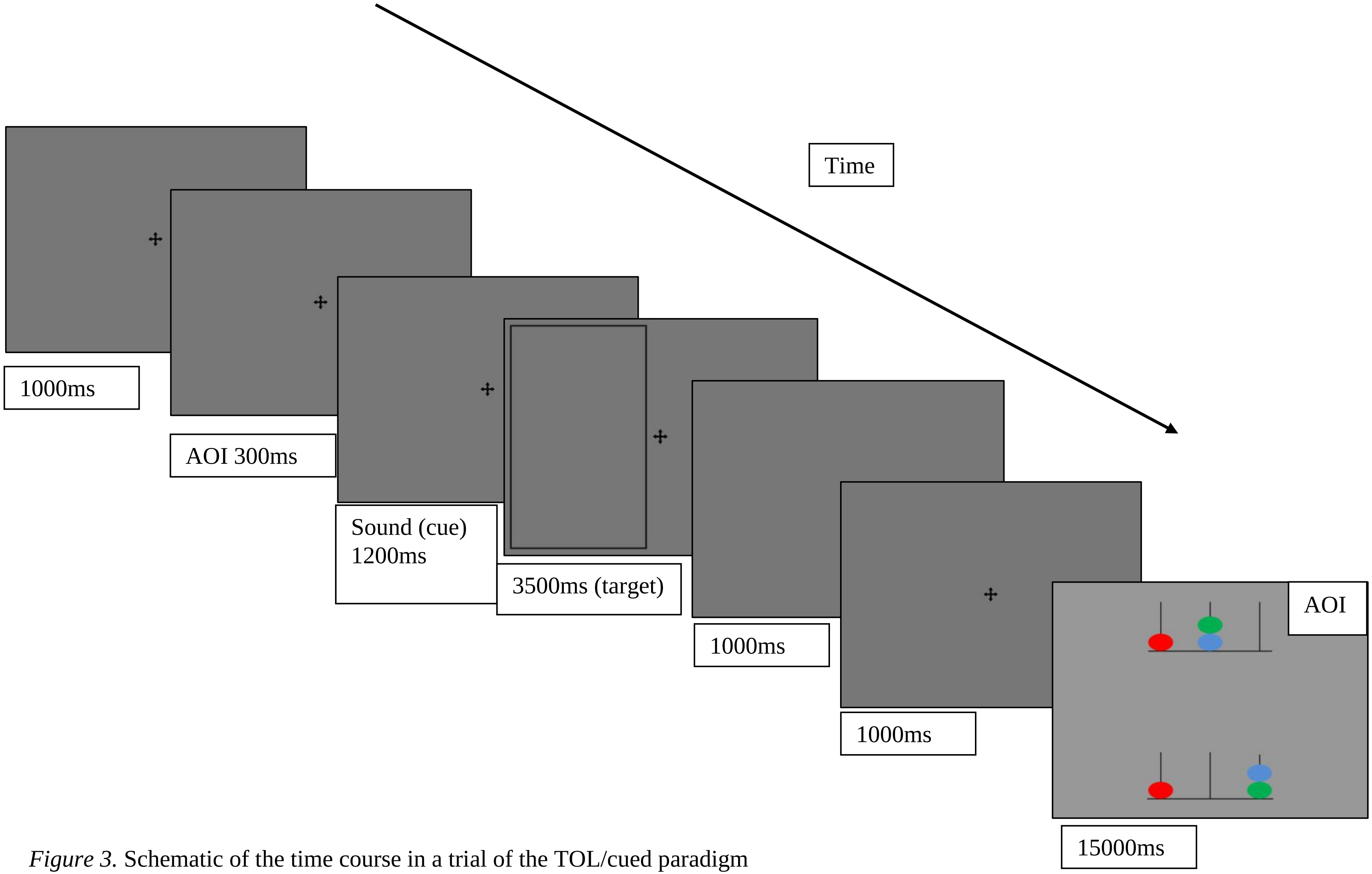

Figure 3. Schematic of the time course in a trial of the TOL/cued paradigm

Visuo-spatial memory task

The VPT assesses non-verbal visual-spatial short-term memory. Participants were presented with matrix ‘checkerboard’ patterns of black and white squares in grids of varying sizes (2x2 to 5x6), with the number of blacked-out squares increasing from 2 through 15 through the course of the test. See Figure 4 for examples of the levels of difficulties of the VPT and Figure 5 display the course of the experiment.

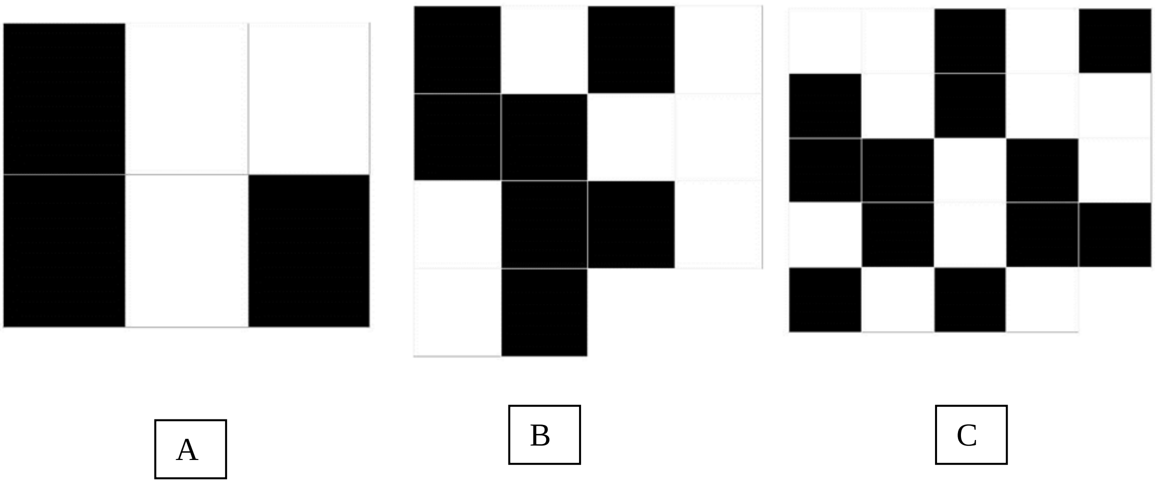

Figure 4. Examples of stimuli at different levels of VPT, with (A) = level 6, (B) = level 14 and (C) = level 24

We were not able to obtain the original VPT and therefore a modified version was created for the present study. The stimuli (i.e. ‘checkerboard’ matrix) were created in accordance with suggestions put forth by Brown, Forbes, and McConnell (2006). They reported that the patterns might resemble figures, images or familiar shapes which might help memory. Thus, the precense of recognisable patterns might indicate that verbal codes (i.e. name of the recognisable pattern) aid memory. If verbal codes are introduced then the test cannot claim to be a test of pure visuo-spatial memory. Before each trial a fixation cross was presented in one of the four corners of the screen for 1000 ms. In order to ensure that the participant looked at the fixation cross a trigger AOI of 300 ms was employed. A trigger AOI starts the subsequent trial if predetermined fixation time is met, i.e. if the participants view the preset area for a fixed number of ms then the following trial is triggered by the program. Following the fixation cross, the patterns was shown for 3,000 ms, and then a ball bouncing around on the screen was displayed for 10,000 ms. The bouncing ball was created using a script in Internet Explorer. The participants were instructed to follow the movement of the ball with their eyes. As previously noted, the purpose of the bouncing ball was to disrupt the afterimage of the presented checkerboard matrix. If they forgot to follow the movement of the ball, the experimenter reminded them. Subsequent to the bouncing-ball the response screen was displayed. A script written for Internet Explorer displayed a white-checkerboard. The participants would use the PC-mouse and click on the grids, the grids would then become black. Participants were instructed to press the F11 key when satisfied with their representation, which caused a new trial to start. The test was terminated if two consecutive errors were made and the test was scored according to the maximum level of 'checkerboard' matrix that was correctly achieved.

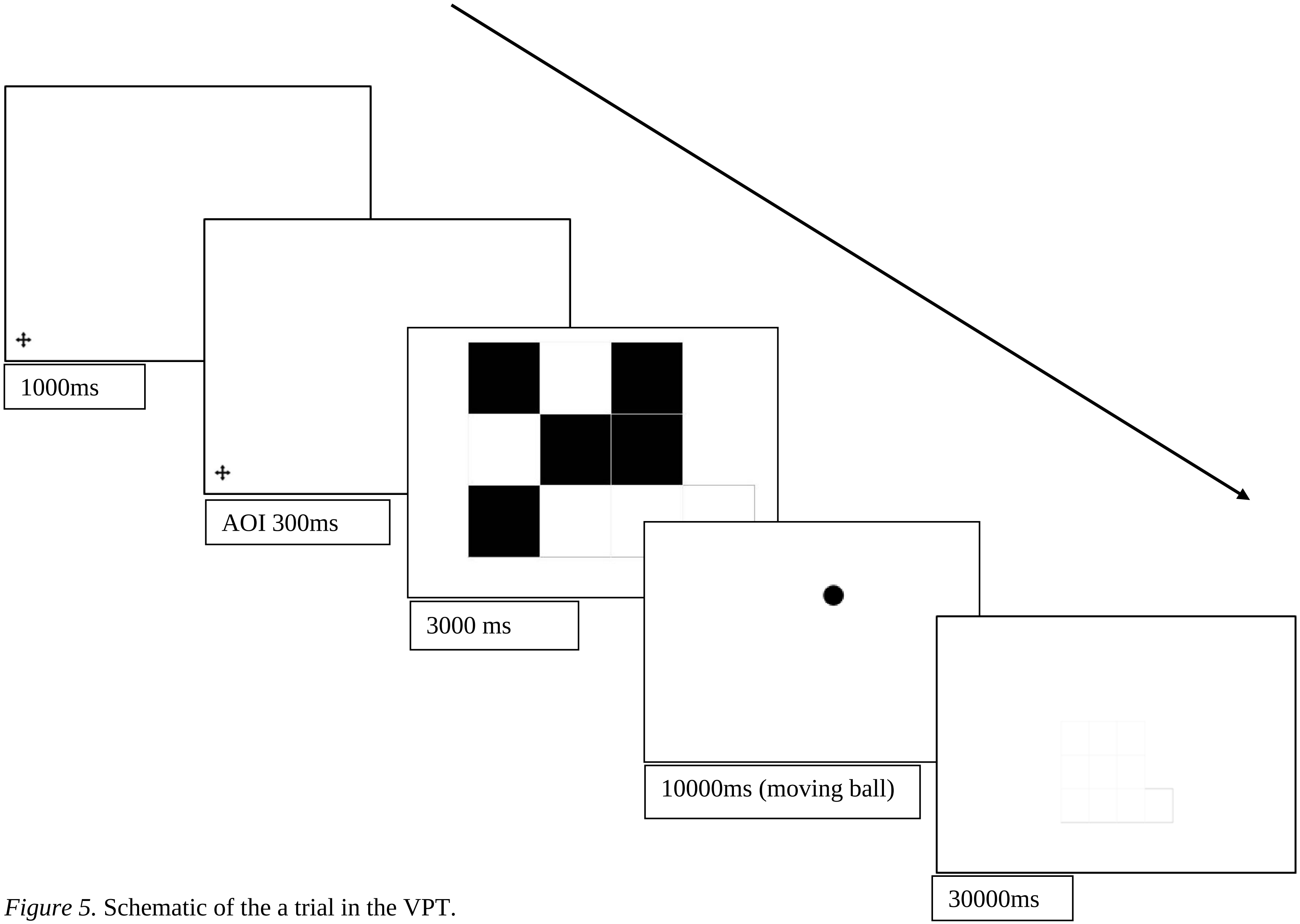

Figure 5. Schematic of the a trial in the VPT.

Multiplication

The multiplication test was used as a control task and as a measure of the effects of cognitive load. The participants were instructed to answer as correctly but as quickly as possible. They were informed they had 30s to solve each question and that they would have to look at the screen in front of them for the entire time. A central black cross was present on a grey screen throughout the entire assessment. They were, however, not specifically instructed to fixate the cross. As soon as they had solved the arithmetical problem, they would report their answer verbally to the experimenter and subsequently press a key ('m'). The key pressing was used as a rough index of response time. The problems were presented auditory using computer speakers. Each problem was given at a 40s interval. The subsequent problem was presented irrespectively whether or not the participants were able to solve the prior problem. The problems were presented at increasing level of difficulty: 3x4, 4x7, 7x8, 8x13, 9x15 and 16x23. It was decided to add 3 problems to the original 5 problems which were assessed in the study by Hess and Polt (1964). Two easier (3x4 and 4x7) and one intermediate (9x15) problems were added to the original 5-problem test. The data was scored according to the number of correct responses on all trials.

Pupil Data Pre-processing

For each participant, a single-average measure of the pupillary diameter was obtained (in pixels) for each baseline presentation and for each subsequent test image. Pixels were averaged across all fixations occurring within each event. In order to obtain a measure of pupillary change as well as to normalize individual differences in physical dimensions of the pupils, the pupillary measurements during the baseline condition were subtracted from the pupillary measurements of the subsequent test images. Scores that were more than ± 3SD away from the mean pupil value were removed from computations.

In addition to pupillary change, the relative number of fixations, and eye blinks for each trial was averaged for each experimental condition. Any data points that were ± 3SD away from the mean were filtered out.

Results

Behavioural data

As shown by independent t-tests and Chi-square analysis, the groups did not significantly differ in terms of gender [χ^2 (1, N = 35) = 0.761, p= .383], age [t(30) = 0.664, p=

.512], or education [$t(30) = 0.664$, $p = .512$]. A filter was used to exclude scores that were more than ± 3SD away from the mean.

Spatial consistency task

The most common mental representations of the calendar among synaesthetes would seem to be either oval or circular (N=16). Other representations included linear (N= 4) or curved linear (N =1). Figure 6 illustrates some of the spatial calendars as constructed by synaesthetes and controls.

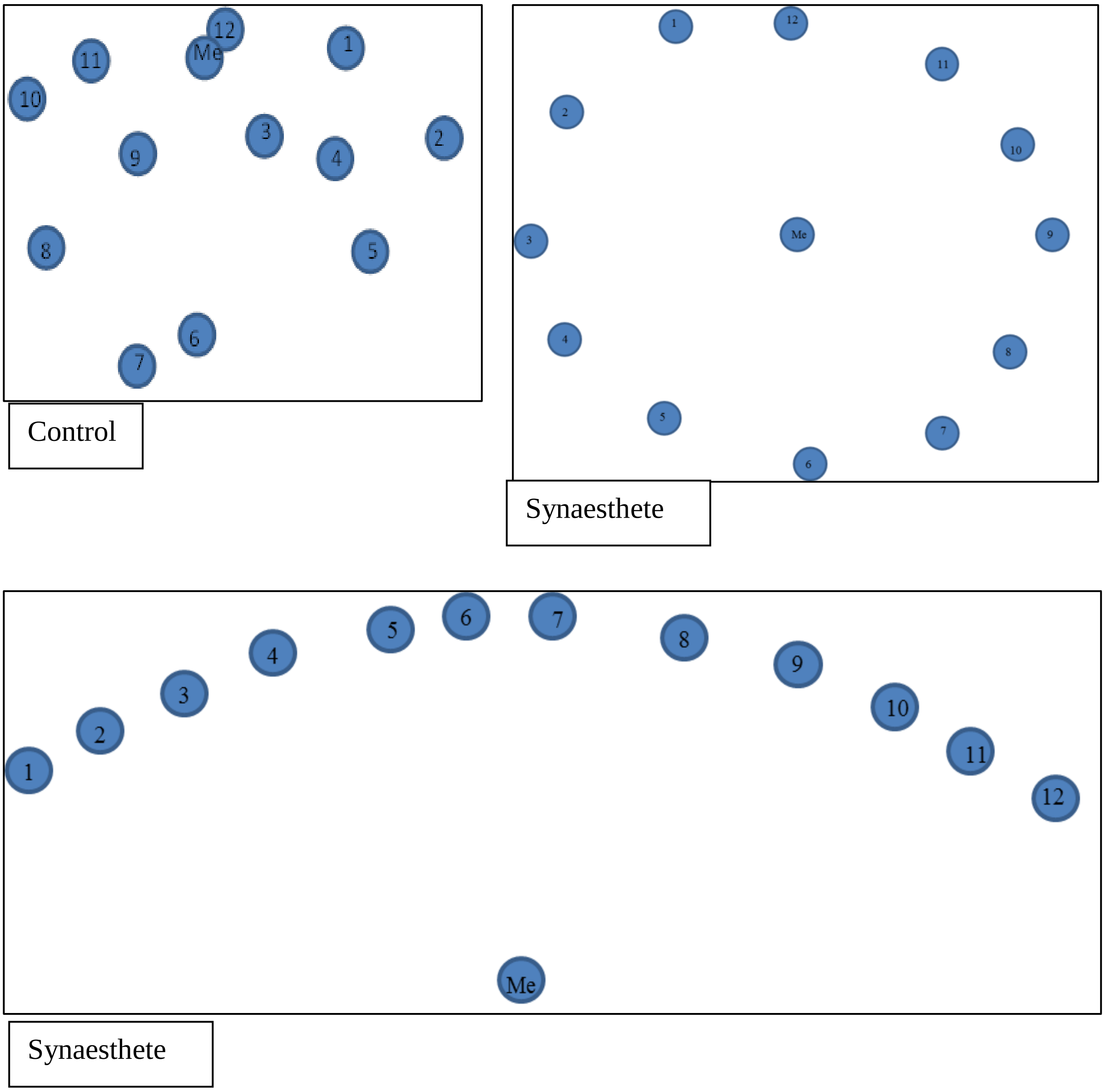

Figure 6. Illustrations of the spatial representations presented by one control participant and two synaesthetes. The numbers represent the months (1=January, 2=February, 3=March, etc).

In order to identify and validate the presence of “true” synaesthesia among our participants, a test-retest of their spatial calendar was conducted. The x-space of the positioning of the dots was used to determine the test-retest reliability of each synaesthete. Two synaesthetes did to conduct the retest due to drop-out of the study. However, the synaesthetic cueing effect clearly validates the individual as a synaesthete. For the reminder of the synaesthetes, the reliability was high with Cronbach’s Alpha ranging from .977 to .994. See Figure 7 for a visual illustration of the overlap between the calendars at test-retest. However, one synaesthete conveyed a negative correlation; the calendar was ordered in a mirror fashion from initial testing. The Cronbach Alpha was -26.592 (r =-.993). Thus, the participant was removed from the synaesthetic group. One control was identified as a possible synaesthete after spatial mapping and RT on the cued paradigm. The participant had a Cronbach’s -Alpha = .991 for the test-retest of their spatial calendar.

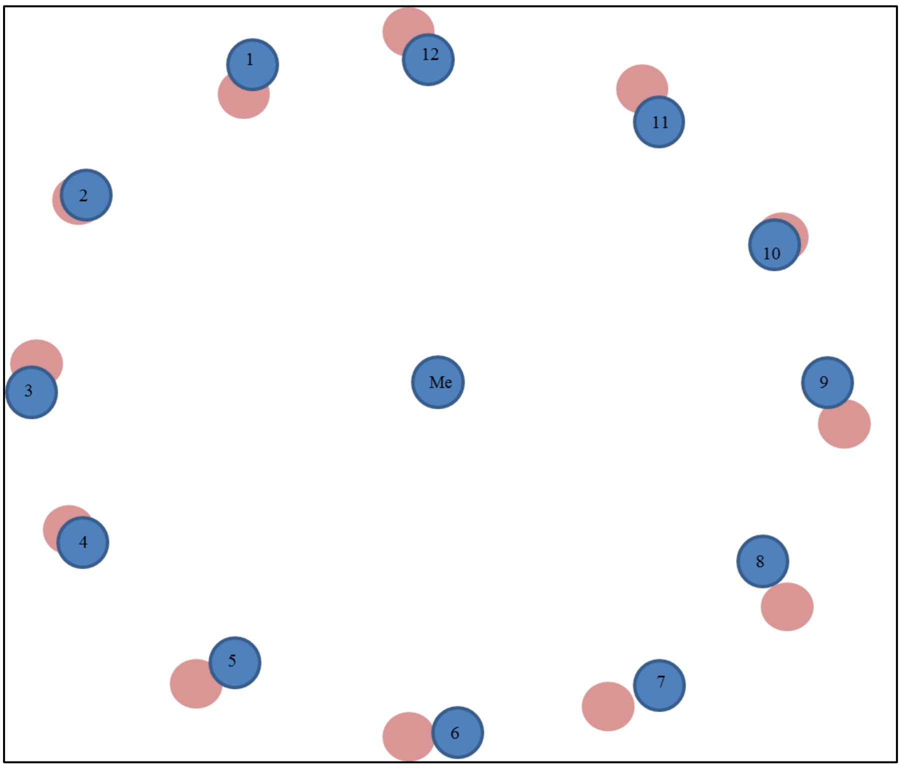

Figure 7. Test -retest representation of one synaesthete’s calendar. The blue circles are at test time 1, the pink circles are at retest, time 2.

CUEing task

The results from the catch trials indicated that all participants were able to follow the task instructions and to withhold their responses. Responses were made on less than 1 % of catch trials. Due to the nature of the spatial layout of six synaesthetes' calendar it was not possible to code the cues as either being valid or invalid (i.e.,, they reported a vantage point of the months so that these appeared in the same line of sight of the synaesthetes). Due to technical difficulties RT data was lost for one synaesthete. Therefore, only 14 synaesthetes were included in the complete analysis. In order to provide a 'validity effect' index from the synaesthetes' RTs, the average 'valid' RT was subtracted from the 'invalid' RT for all the synaesthetes. For the controls an average RT was calculated using the spatial position of the cue. The cue should not influence the RT, and the RT for the right cue was subtracted from the left RT. An independent-group t-test was then used to assess differences between synaesthetes and non-synaesthetes as a function of valid/invalid cues. The difference was non-significant [$t(23)=1.525$, $p= .139$].

Separate t-tests were also conducted for each participant so as to reveal the proportion of participant showing a significant cueing effect at the individual level. Three synaesthetes (i.e., 20% of the group) displayed a valid cueing effect, whereas none of the controls showed a cuing effect. Importantly, no synaesthete showed, according to the t-tests a significantly faster response to invalid than valid cues. Hence, the present results are consistent with the expectations that time-space cues do affect attention in the predicted direction, although these effects were very weak at the group level and could be revealed clearly only for a small percentage of the participants. The data for the all of the synaesthetes are presented in Table 1.

Table 1

Cuing effect of the individual synaesthetes

Synaesthete ID	*t*	*α*	SE	95% CI LL	95 %CI UL
101	.457	.652	26.008	-40.332	63.922
102	-.778	.440	16.928	-47.080	20.742
103	.640	.526	40.112	-55.402	106.735
105	.-1.104	.315	19.317	-58.284	19.111
106	-4.500	.000**	84.496	-549.042	-211.443
112	.145	.885	39.876	-74.053	85.649
114	-1.730	.089	18.864	-70.405	5.143
115	-.807	.432	19.572	-54.936	23.365
116	-0.915	.364	18.649	-54.442	20.305
125	.439	.662	43.549	-68.004	106.277
126	.537	.593	36.940	-53.902	93.603
127	-2.336	.024*	33.614	-146.083	-10.981
128	-1.745	.086	47.200	-176.583	11.894
131	-2.751	.008**	30.509	22.835	145.022

Note. CI = confidence interval; LL= Lower limit; UL = Upper Limit. SE= standard error, *Significant at α=.05, **significant at α=.01

In order to assess whether the heterogeneity amongst the synaesthetic group influenced the reaction time measures, the group was divided in three: “strong” synaesthetes (*N*=3) , “weak” synaesthetes (*N*=6) , “unclear” synaesthetes (*N*=5). The unclear group does not necessarily mean that these participants are not experiencing synaesthetic space forms but only that their synaesthetic experience might not influence or have an impact on attention. The percentage of synaesthetes identified as “strong” synaesthetes were 20%. We considered whether this percentage of “strong” synaesthetes could occur merely by chance or in an artificial way. It could be that be that strong synaesthesia occurred in this group by chance. In order to dismiss the likelihood of it occurring by chance lies with the low prevalence of “verified” versus “possible”, and non-synaesthetes reported by Ward and Simner (2005) who reported 2.19%

verified synaesthetes within their sample, in contrast to our figure of 20%. In order for this figure to occur by chance one would need to assume a prevalence rate of 1.5% [1]

VPT

Two participants, one synaesthete and one control, were identified as outliers while data for one participant were lost due to technical difficulties. The mean score for the synaesthete was 14.5 (SD=2.8, range=10-20) and the mean score for the non-synaesthete was 13.8 (SD=2.4, range=8-16). The difference between the two groups was non-significant, according to an independent samples t-test [$t(30) = 0.664$, $p = .512$]. This finding goes against our predictions as it indicates that synaesthetes do not perform at a superior level in this task compared to the control participants.

Multiplication

Two participants, one control and one synaesthete, were identified as outliers with extreme negative scores and removed from further analyses. The mean correct score for the synaesthete was 5.34 (SD=1.25, range: 3-7) and the mean score for the non-synaesthetes was 4.50 (SD=1.56, range: 2-7). In accordance with our hypothesis, there was no difference between the two groups since the result was non-significant in an independent samples t-test [$t(31) = -1.281$, $p = .210$].

TOL

The mean correct response for the synaesthetes at each level of TOL is shown in Table 2. Two participants, one control and one synaesthete, were removed because they were outliers with scores in a negative direction of the reminder of the sample.

[1] The calculations were adapted from (Ward & Simner, 2005) and are as follows. We assumed that 15 synaesthetes were tested for the presence of a "strong" form of synaesthesia (based on our own data).Then one might ask what prevalence rate *x* is needed to generate a probability of 0.20 of finding at least 1 other "strong" synaesthete if one assumes that the presence of strong synaesthetes are independent of the other forms synaesthesia? The probability of finding none "strong" synaesthete is 0.80 (=1 – 0.20), and this figure is equivalent to $(1-x)^{15}$; thus x is $(1-.80^{1/15}) = 0.015$.

Table 2

Mean Correct Responses for each level of the TOL

	Synaesthetes		Controls	
	Mean	SD	Mean	SD
Level 2	20.8	1.39	20.6	1.19
Level 3	20.0	1.96	17.9	2.06
Level 4	20.0	2.14	17.3	2.13
Level 5	11.3	3.18	11.0	2.81

Note. SD= standard deviation.

A two-way repeated measures analysis (ANOVA) was used to compare the number of correct responses at each level TOL of the synaesthetes and controls. The between-group means were non-significant [$F(1,31)=0.230$, $p=.635$].

The interaction effect between level of TOL and synaesthesia was not statistically significant, $F(3,93)=.701$, $p=.554$, partial eta squared = .022. There was a statistically significant main effect for level of TOL [$F(3,93)=135.274$, $p=.001$, partial eta squared = .815]., indicating a significant decrease in the number of correct responses as a function level of TOL

Executive functions/task switching

We further explored the impact of level of difficulty in the TOL task on the RT in relation to valid/invalid cues. The RT of the cued paradigm for was coded according to the preceding level of TOL. The valid RT was further subtracted from the invalid RT to create a "validity effect" measure. Two linear regression analyses were conducted, one for each group. We then calculated the z-score to determine whether the regression slopes were significantly different. There was no significant difference between the valid/invalid RTs in synaesthetes as a function of level of TOL. There was no significant difference in the regression slopes between synaesthetes ($r=.110$, N=52) and the controls ($r=.135$ N = 54), with a z-score = 0.13, $p= .448$.

Pupillary change analysis

TOL

Due to technical issues behavioural data were not recorded for two participants, one control and one synaesthete. Pupillometry was recorded, but it is not meaningful to analyze, given the differences in luminance in each trial. However, number of fixations could be used as an index of cognitive load. A two-way repeated measures analysis (ANOVA) was used to compare the number of fixations at each level TOL of the synaesthetes and controls. The between-group means were non-significant [$F(1,33)=0.070$, $p=.793$].

The interaction effect between level of TOL and synaesthesia was not statistically significant, $F(5,105)=.895$, $p=.497$, partial eta squared = .041. There was a statistically significant main effect for level of VPT [$F(5,105)=2.692$, $p=.025$, partial eta squared = .114]. The finding indicates an increase in cognitive load as a function of increasing level of difficulty.

Though the within-group analysis indicated a significant effect were significant indicating an increase in the number of fixations as a function level of TOL [$F(3,33)=0.199$, $p=.001$]. This was in accordance with our hypothesis as increasing level of difficulty requires more moves, thus the number of fixations should increase respectively.

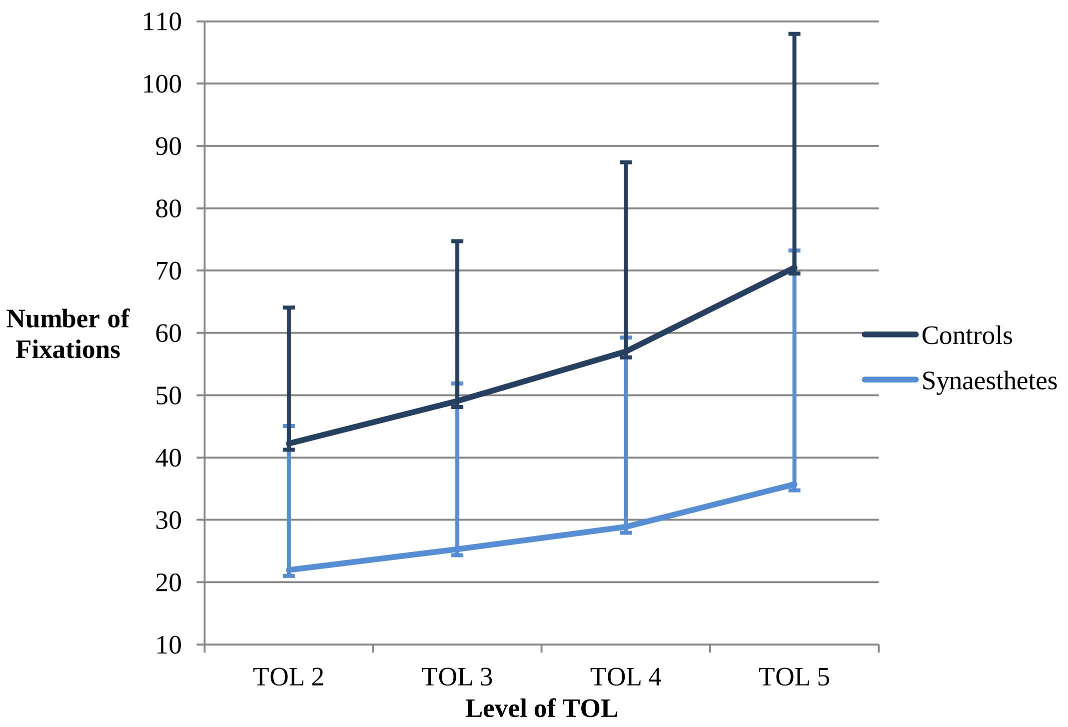

Figure 7. Number of fixations across levels of TOL. Bars indicate 95% confidence intervals for within-subject designs (Cousineau, 2005; Loftus & Masson, 1994).

VPT

A limited number of participants (*N*=10) had correct responses above the 14 level of difficulty, thus in order to compare the groups the analysis were conducted on levels 4 through level 14 (i.e. level 4, 6, 8, 10, 12 and 14). Due to difference in luminance between the encoding phase and the retrieval phase the number of fixations was used as an index of cognitive load, see Figure 8 for an illustration of the mean number of fixations as function of level of VPT. A two-way repeated measures ANOVA was used to compare the group difference in number of fixations as a function of increasing level of difficulty. The between group means were non-significant [$F(1,21)=0.001$, $p=.973$, partial eta squared = .001]. The finding is not in accordance with our hypothesis, though the finding is expected since the behavioural data indicated a non-significant difference in number of correct trials between controls and synaesthetes.

The interaction effect between level of VPT and synaesthesia was not statistically significant, $F(5,105)=.259$, $p=.934$, partial eta squared = .012. There was a statistically significant main effect for level of VPT [$F(5,105)=12.333$, $p=.001$, partial eta squared = .370]. The finding indicates an increase in cognitive load as a function of increasing level of difficulty.

To assess whether controls experienced more cognitive load during the initial presentation of the VPT problem a two-way repeated measures ANOVA was used to compare the group difference in pupil change as a function of increasing level of difficulty. The between group means were non-significant [$F(1,21)=1.312$, $p=.265$, partial eta squared= .059]. The finding is not in accordance with our hypothesis, though the finding is expected since the behavioural data indicated a non-significant difference in number of correct trials between controls and synaesthetes.

The interaction effect between level of VPT and synaesthesia was not statistically significant, $F(5,105)=.895$, $p=.497$, partial eta squared = .041. There was a statistically significant main effect for level of VPT [$F(5,105)=2.692$, $p=.025$, partial eta squared = .114]. The finding indicates an increase in cognitive load as a function of increasing level of difficulty.

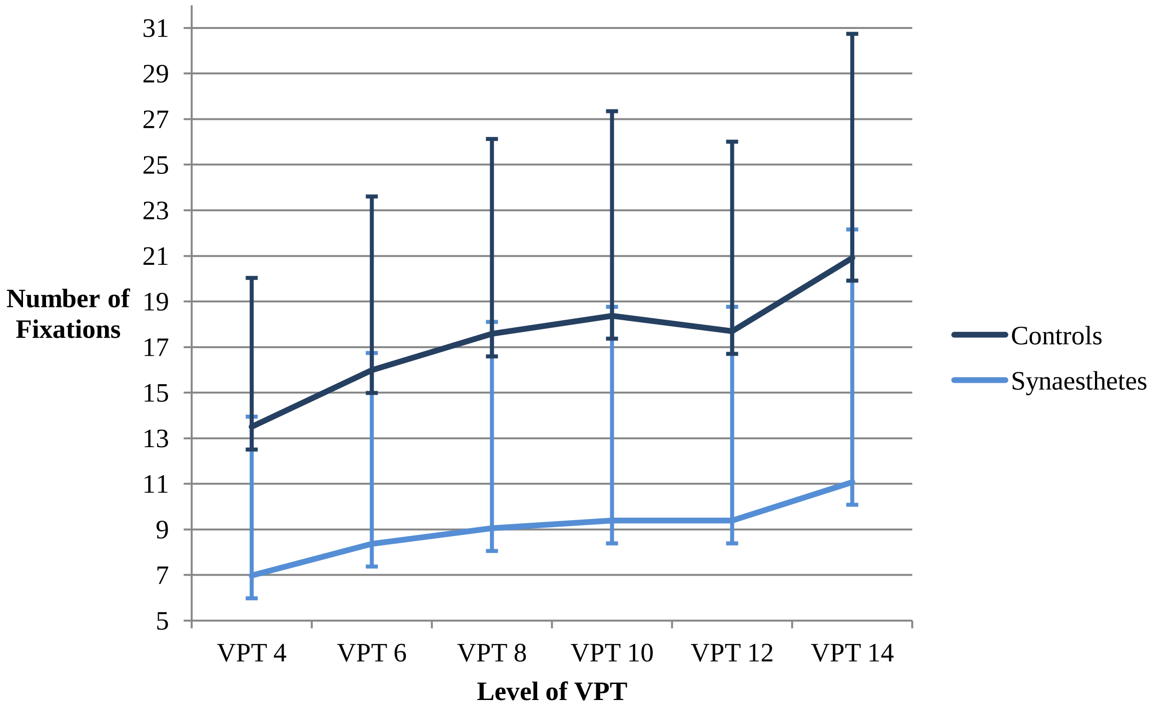

Figure 8. Number of fixations across increasing level of VPT. Bars indicate 95% confidence intervals for within-subject designs (Cousineau, 2005; Loftus & Masson, 1994).

CUEing

Due to technical difficulties rendering a large amount of missing data (above 50%) one participant (synaesthete) was excluded from further analyses. Also some synaesthetes presented with spatial representations of calendars that were not possible to score as valid/invalid, thus they were omitted from the analysis related to valid/invalid cues. In relation to the behavioral analyses, RT-data for two particpatipants were lost due to technical analyses. However, the pupillomitry data was recorded and the data was included in this analyses. In summary, only 15 synaesthetes were included in the analysis.

A two-way repeated measures ANOVA was performed with group (synaesthetes, control) as the between-factor, the cue (valid, invalid) as within-group factor and pupil change as the dependent variable. The ANOVA revealed a non-significant main effect for cue, $F(1,27) = .620$, $p = .438$, partial eta squared = .022. Furthermore, the ANOVA revealed a statistically non-significant interaction effects of cue on group dependence $F(1,27) = .044$, $p = .835$, partial eta squared = .002.

The repeated measures ANOVA indicated that there was not a statistically significant difference in pupil change between the groups $F(1,27) = .216$, $p = .646$, partial eta squared =

.008. These findings are not in accordance with our hypothesis, however, the pupil change data reflect the results indicated by the behavioural measures.

Multiplication

Error trials were not included in the analysis (Easy= 6.67%, Intermediate= 25.71%, and Difficult=67.14 %). Furthermore, 6 participants (17.14%) were excluded due to missing data (4 synaesthetes and 2 controls) rendering 29 participants for further analyses.

A two-way repeated analysis of variance measure (ANOVA) was used to compare the cognitive load, as measured by pupil change, of synaesthetes and non-synaesthetes. The between group factor was group-dependence (i.e. control or synaesthete) and the within-group factor was level of difficulty of the mathematical task (i.e. 3x4, 4x7, 7x7, ...) The ANOVA indicated that there was no statistically significant difference between groups [$F(1,27)=0.067$, $p=.798$]. This was in line with our predictions.

The interaction effect between groups and level of multiplication was non-significant, [$F(6,162)=0.556$, $p=.462$, partial eta squared = .020]. There was a statistically significant main effect for level of multiplication [$F(6,162)=6.599$, $p=.016$, partial eta squared = .196]. Thus, it is reasonable to argue that the both groups experienced an increase in cognitive load. This finding is in agreement with the now classic study by Hess and Polt (1964).

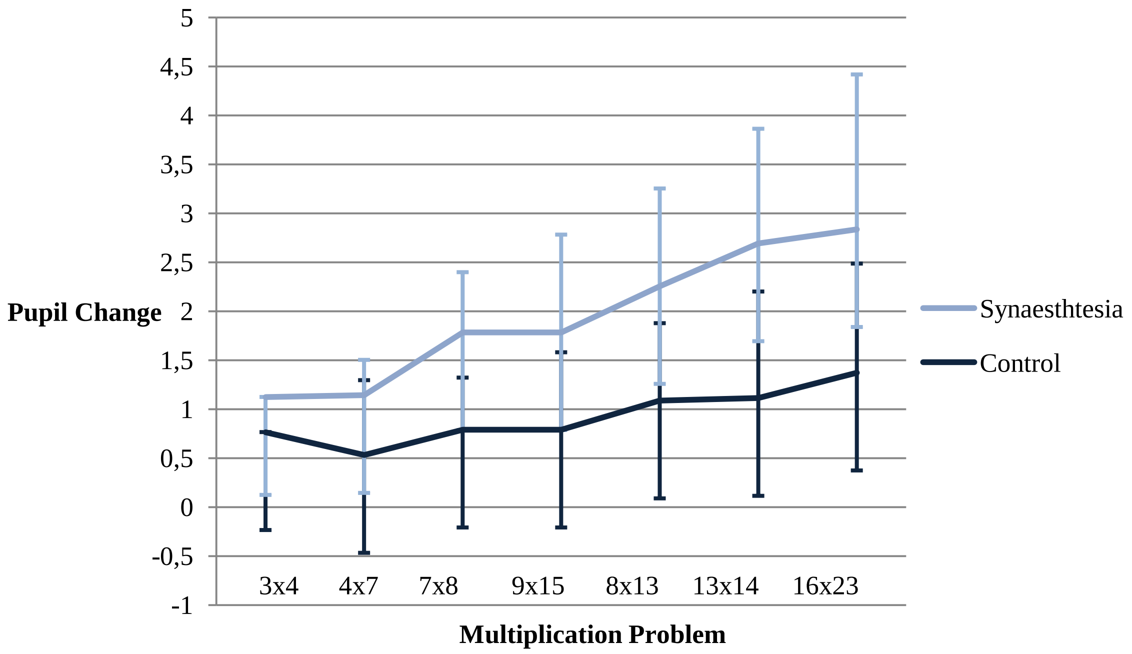

Figure 9. Differences in pupil size (in pixels) across the seven mathematical problems. Bars indicate 95% confidence intervals for within-subject designs (Cousineau, 2005; Loftus & Masson, 1994).

Discussion

The dual aims of this study were to examine visual-spatial memory in time-space synaesthesia and to explore the presence of heterogeneity within this group. We found that synaesthetes – in disagreement with our hypothesis – were not superior in the visuo-spatial memory task (VPT) in comparison to the control group. Our results do not converge with previously findings of superior visuo-spatial memory abilities in time-space synaesthetes (Mann et al., 2009; Simner, Mayo, et al., 2009). Though, Simner, Mayo, et al. (2009) employed a small sample size for assessing VPT in synaesthesia (4 synaesthetes were compared to a norming population of 345 individuals). It is possible that the results may be contaminated by demand characteristics when a small sample size is utilized. Mann et al. (2009) on the other hand had a large sample size (*N*=50), but synaesthetes were not actively recruited. A semi-structured interview was used to determine the likelihood of the participants being time-space synaesthetes. The semi-structured interview did not include an assessment of consistency. This might pose as a limitation because, as mentioned previously, the synaesthtetic experience may be present in some form in all individual but synaesthetes differentiate themselves from non-synaesthetes in terms of consistency and vividness of the synaesthtetic sensation.

Our results are, however, in line with Rizza and Price (2012) who argued that time-space synaesthetes do not have superior spatial imagery. Though, they also suggested that synaesthetes have a superior visual imagery. One possible account for our findings is that any advantage the time-space synaesthetes might have in terms of enhanced visual imagery were reduced due to the introduction of the interleaved (bouncing ball) task between encoding and retrieval. Furthermore, Simner, Mayo, et al. (2009) put forth the idea that the superior skills synaesthetes might indicate an enhanced ability to mentally retrieve and recall visual structures. The original VPT does not include a distracting visual factor between encoding and retrieval and is a purer visual recall/imagery tests. Thus, it is possible that the bouncing ball might have eradicated any memory advantage the synaesthetes might have. As previously noted, it has been suggested that eye movements during mental imagery have a functional role (Laeng & Teodorescu, 2002). If synaesthetes have superior mental imagery, this advantage might have been disrupted since the bouncing ball might have prevented the rehearsal.

Future studies should examine whether the ball reduces the advantage the synaesthetes might have. This could extend to grapheme-colour where one could introduce a distracting task in tests for verbal memory.

Our results point to an intriguing interpretation that synaesthesia might not be an all-or-nothing phenomenon, but rather there appears to be a continuum which influences the synaesthetic experience. The analyses of RT in relation to cued month paradigm at an individual level suggested that there is heterogeneity within this group. Only three synaesthetes showed a significant cueing effect but this was in the predicted directions in all cases. Importantly, none of the controls displayed a cuing effect. This finding is line with previous studies reporting behavioural differences between synaesthetes (Brang, Teuscher, Miller, Ramachandran, & Coulson, 2011; Brang et al., 2010; Ward, Li, Salih, & Sagiv, 2007). The results by Brang et al. (2010) also support a continuous view of synaesthesia. Furthermore, heterogeneity and individual difference within the synaesthetic group has also been reported by Smilek et al. (2007). They found individual differences of time-space synaesthesia of attention, which is in line with our reported results. They reported that two of the four synaesthetes showed strong influences of their synaesthesia on attention. A weaker influence of time-space synaesthesia on attention was found in one participant. One of the tested synaesthetes had an indistinguishable cuing effect in relation to the control participants. However, all synaesthetes conveyed high test-retest spatial consistency. We also report on high test-retest spatial consistency of the synaesthetes spatial calendar. Though, as mentioned, there were large individual differences in relation to attentional bias elicited by the month-cue.

One possible account for the observed heterogeneity could be that some synaesthetes might have a more vivid experience than others which in turn influences attention to a greater extent than for synaesthetes with a lesser degree of vivid experience. Furthermore, Berteletti et al. (2010) advocated the need to distinguish between 'synaesthetes' and pseudosynaesthetes'. Pseudosynaesthetes only mimic synaesthesia since they have acquired their associations through repeated learned associations. They differentiated between conscious and non-conscious association. They further suggested that a genetic component, in combination with associated learning, differentiates synaesthetes and non-synaesthetes. As previously mentioned, Brang and Ramachandran (2008) suggested a genetic expression of synaesthesia. The genetic component might also influence the observed heterogeneity as the variation might be related to whether certain thresholds (i.e. genetic expression) are met. In addition, it has been suggested the synaesthesia may be due to reduced "pruning" of cortical connections and that this reduction in pruning might be influenced by a genetic predisposition (Mondloch & Maurer, 2004; Ramachandran & Hubbard, 2001). Diffusion tensor imaging (DTI) studies have also identified subtypes of synaesthetes. Rouw and Scholte (2007) reported a difference in structural connectivity between ‘projectors’ and ‘associators’ with increased hyperconnectivty for ‘projectors’. The ‘projectors’ experience the synaesthetic sensation as a ‘real’ sensation, whilst ‘associators’ experience the sensation with the ‘mind’s eye’. The finding indicates that greater connectivity is associated with a more ‘real’ perception of the synaesthetic sensation and that the synaesthetic sensations might be influenced by variations in structural connectivity. Additionally,Dixon et al. (2004) reported a behavioural difference between associators and projectors on a synaesthetic Stroop task. In conjunction with behavioural data, neurological results indicate that there is heterogeneity or variation among synaesthetes. Future research should be set out to explore the diversity and heterogeneity within this population.

The present findings, taken together, highlight the importance for future research to consider time-space synaesthesia as a phenomenon on a continuum and to acknowledge the heterogeneity and individual differences within the group since it might influence the results. Furthermore, the results indicate that the spatial consistency test-retest, which is the most commonly used test to validate time-space synaesthetes, might not be sensitive enough to detect individual differences that matter for behavior and cognitive functioning.

We found no difference in cueing effect between synaesthetes and controls. There are two possible accounts for this finding. The first account is related to heterogeneity within the synaesthetic group. As previously discussed there are individual differences between synaesthetes and, despite reporting a high test-retest spatial layout, the synaesthetic sensation might not sufficient to influence behaviour. Thus, future research ought to examine whether there is a difference in cuing effect between “strong” synaesthetes, “weak” synaesthetes and controls.

The second account is related to attentional load and executive functioning. Our findings may be interpreted in line with the results reported by Mattingley et al. (2006). They presented participants with a dual-task paradigm and noted that the synaesthesia sensation was diminished due to increasing attentional load. It is reasonable to argue that we also employed a dual-task (i.e. the TOL) and that it was too attention demanding so that the synaesthetic sensation was suppressed. The attentional load stimulus employed by Mattingley et al. (2006) was an outline of a diamond-shaped figure where every side contained a gap. The participants had to judge which side of the diamond had the largest gap, a task which only requires estimating properties related to the stimuli, it does not require any mental manipulation. The size of the gap differentiated between the high-load and the low-load conditions. In comparison, the TOL required mentally manipulating images, constantly updating working memory whilst holding relevant information active.

We reported an increase in cognitive load, as index by pupil change, for the multiplication test and the VPT. Furthermore, there was a significant increase of number of fixations as a function of level of TOL. Thus, despite not reporting differences between the groups, we can be confident that the tests assessed cognitive load and therefore that the present results are valid. Importantly, the results are convergent with the results by Hess and Polt (1964) which indicate that pupil change is a valid measure of cognitive load.

Limitations

There are a few limitations associated with the current experiment and results that should be taken into consideration. First, we were not able to obtain the original VPT, we employed an adapted version. Therefore, we cannot directly compare these results with previous studies using the original VPT. Furthermore, the construct validity of our version of the VPT has not been assessed.

The second limitation is associated with the subjective reports of synaesthesia, as it is mainly based on self-reports. Currently there is no standardised, validated behavioral measure that indicates whether an individual has synaesthesia. We had to rely on self-reports and spatial consistency test. Time-space synaesthesia is a difficult phenomenon to assess and validate. We cannot be entirely certain that we are assessing only time-space synaesthetes and as (Berteletti et al., 2010) pointed out there might exist pseudosynaesthetes which might have contaminated the cued effect. Thus, there is a call for future research to develop more consistent means to assess time-space synaesthesia, and synaesthesia in general.

The TOL was partly introduced to reset the spatial calendar of the synaesthetes between each cued month trial. We did not, however, assess whether the spatial calendar actually was resetted between trials. This was only inferred by asking how the participants perceived the task. Thus, we need to be cautious in terms of drawing an inference based on the spatial calendars being resettled between each cued month trial.

The fourth limitation that needs to taken into consideration is that we did to differentiate whether the synaesthetes were ‘projectors’ or ‘associators’. As previously discussed, this difference might influence the synasthetic sensation. Therefore, it might pose as confounding variable we did not control for. As previously noted, there is a call for future studies to examine the individual differences within time-space synaesthtesia.

Conclusions

In this study, we reported evidence indicating heterogeneity and individual differences within the time-space synaesthetes which influence the synaesthtic sensation. Furthermore, our findings indicate that increased attentional load can influence (decrease) the synaesthtetic experience.

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